4. MATERIALS FOR AIR HANDLING, HOT SECTION, AND STRUCTURAL COMPONENTS

A. High-Temperature Advanced Materials for Lightweight Valve Train Components

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Objective

- Evaluate prospective lightweight valve materials and determine feasibility of implementation in heavy-duty diesel and natural gas applications.

Approach

- Design, procure, and evaluate γ-phase titanium aluminide (TiAl) and silicon nitride (Si_3N_4) heavy-duty engine valves.
- Demonstrate performance and durability advantages by performing 1000-h durability test on valves in a Caterpillar G3406 natural gas engine.
- Develop finite-element analysis (FEA)-based life prediction model (NASA CARES/Life) that will generate life prediction curves for advanced valve materials.
- Evaluate the thermal, chemical and mechanical properties of TiAl and Si_3N_4 that are critical to on-engine valve performance and durability.
- Investigate manufacturing considerations (i.e., machinability and quality inspection technique) of these novel materials.

Accomplishments

- Procured 12 TiAl and 45 Si_3N_4 heavy-duty engine valves.
- Performed pretest characterization on all valves [laser-scatter nondestructive evaluation (NDE), dimensional check with coordinate measuring machine, surface roughness].
- Completed preliminary life prediction model for Si_3N_4.

- Kicked-off studies to examine friction, wear, corrosion, and machinability characteristics of TiAl.
- Donated a Caterpillar C15 ACERT™ engine to the National Transportation Research Center (NTRC) for future component testing.

Future Direction

- Complete current G3406 engine test on TiAl and Si_3N_4 valves;
  - perform laser scatter NDE scans to track crack/defect propagation;
  - perform fast fracture on specimens extracted from the valves to determine retained strength;
  - correlate results with life prediction model.
- Procure additional TiAl valve blanks for second round of engine tests; will use life prediction model as a design tool to optimize valve geometry.
- Refine NASA/CARES Life prediction model to include non-axisymmetric deformation modes, enable TiAl modeling, and evaluate Probabilistic Design System (PDS) methodology.
- Extend friction, wear, corrosion, and machinability studies of TiAl.

Introduction

Valve train components in heavy-duty engines operate under high stresses, at elevated temperatures, and in severely corrosive environments. Structural ceramics and emerging intermetallic materials are highly corrosion and oxidation resistant and possess high strength and hardness at elevated temperatures. These properties are expected to allow higher engine operating temperatures, lower wear, and enhanced reliability. In addition, the lighter weight of these materials (~50% of production alloys) will lead to lower reciprocating valve train mass that could improve fuel efficiency.

Over the past decade, the automotive engine industry has demonstrated moderate success with TiAl as a valve material. Eylon et al.[1] demonstrated a 2% fuel savings on a Chevrolet Corvette that ran for 25,000 km with TiAl valves. This fuel efficiency increase is attributed to the decrease in valve train parasitic frictional losses. In another study with TiAl valves, Maki et al.[2] demonstrated a 1000-rpm increase in over-speed performance on a Nissan VRT35 engine. This capability would allow more efficient engines to operate in more demanding regimes. The current research and development program at Caterpillar, Inc., extends this body of knowledge from the automotive community and examines TiAl and Si_3N_4 in the context of heavy-duty diesel and natural gas engine environments.

The valve train material development effort will provide the materials, design, manufacturing, and economic information necessary to bring these new materials and technologies to commercial realization. With this information, component designs will be optimized using probabilistic lifetime prediction models, and validated in rig bench tests and short- and long-term engine tests. After establishing proof-of-concept with valves, this design approach will be applied to other components made from high-temperature materials.

Approach

Because the broad goal of this project is to evaluate TiAl and Si_3N_4 materials for use in valve applications, many perspectives must be considered. As such, there are several facets to this project. The primary thrust toward component validation is achieved by fabricating TiAl and Si_3N_4 valves and testing them on a Caterpillar G3406 (in-line 6 cylinder) natural gas engine. Previous annual reports documented the design process used to modify the current baseline metallic valve to accommodate the limited ductility of ceramic and intermetallic materials.[3] For example, the head dimensions were changed to reduce the stress concentration experienced in the fillet radius. Silicon nitride and TiAl valve blanks were formed, rough machined, friction welded to a Ti-6Al-4V shaft (TiAl only), and finish machined.

A parallel effort to develop a design tool for high-strength, brittle materials is also being pursued. A FEA-based life prediction code (NASA CARES/Life) is used to evaluate component design and generate life prediction curves. This approach uses material properties and thermo-mechanical boundary conditions as the primary inputs. A probability-based code then calculates the accumulated damage through the life of the valve and creates a life prediction curve.

A variety of other studies contribute to the understanding of the behavior of TiAl and Si_3N_4 and how they may perform in an engine environment. Several studies examine the fundamental properties of the materials: tensile strength, creep strength, thermo-physical properties, friction coefficient, wear resistance, oxidation resistance, and corrosion resistance. Two other studies examine the manufacturability of the materials: the effect of machining damage on fatigue resistance and a NDE technique to evaluate surface quality.[4]

Results

Valve fabrication

Twelve TiAl and forty-five Si3N4 valves were fabricated and are under final preparations before engine testing. Figure 1 shows the steps of the fabrication process for a TiAl valve. Once the design was finalized, the geometry was sent to the suppliers for blank fabrication. The valve is then rough machined and friction welded to a Ti-6Al-4V valve. This friction weld procedure is performed for three reasons: (1) cost effectiveness, (2) difficulty in maintaining the straightness specification on castings with high aspect ratio and (3) high-temperature strength is not required in stem. The final procedure, finish machining, is required to minimize the probability of a brittle failure caused by surface defects.

As was noted in this program's previous annual report[5] a supplier oversight resulted in incorrect surface finish that resulted in an early life failure on an impact rig. Subsequently, the valves were returned to the supplier for corrective finish machining. It is clear from the laser scatter NDE scans (Figure 2) that the majority of the machining damage was removed after the second finish machining procedure.

Additional preengine test characterization was performed on all valves. A coordinate measuring machine (CMM) was used to ensure that the valves met the dimensional specifications. Also, a profilometry scan was performed on several critical sections of the valves to verify that finish machining achieved the necessary surface roughness. It was confirmed that the surface roughness specification was met for nearly all of the measured regions on all of the valves.

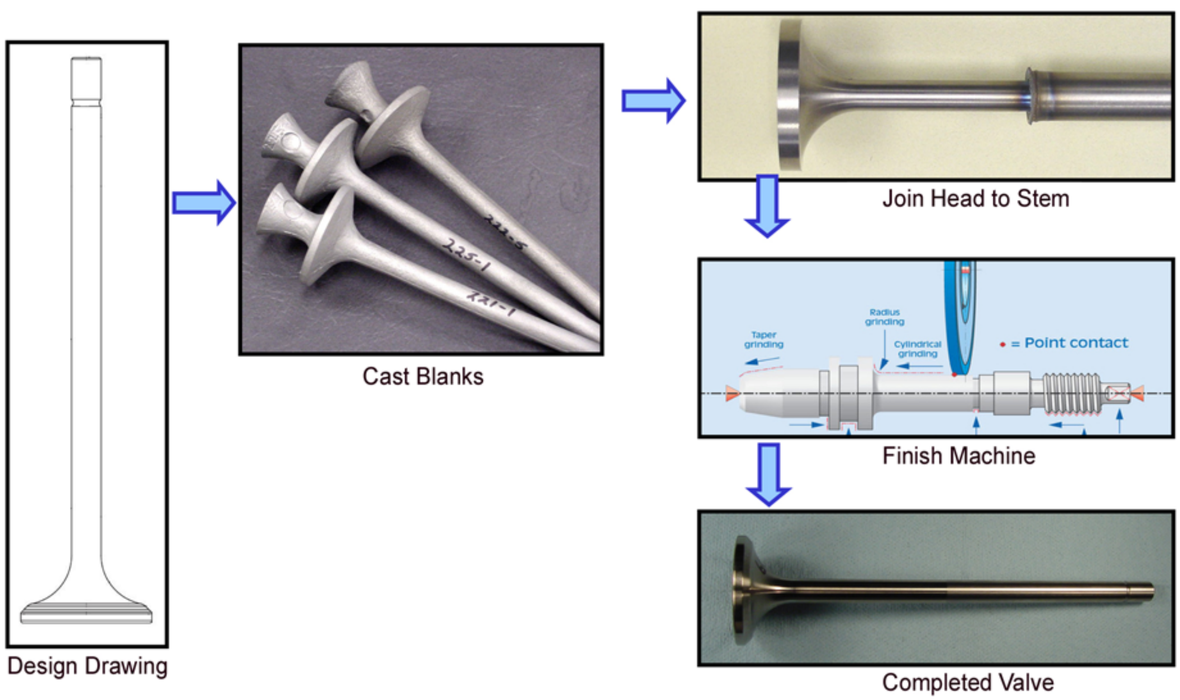

Figure 1. Critical steps of the fabrication process for a TiAl valve. Si_3N_4 valves are subject to every step except the joining of the head to stem because they are formed as a single piece.

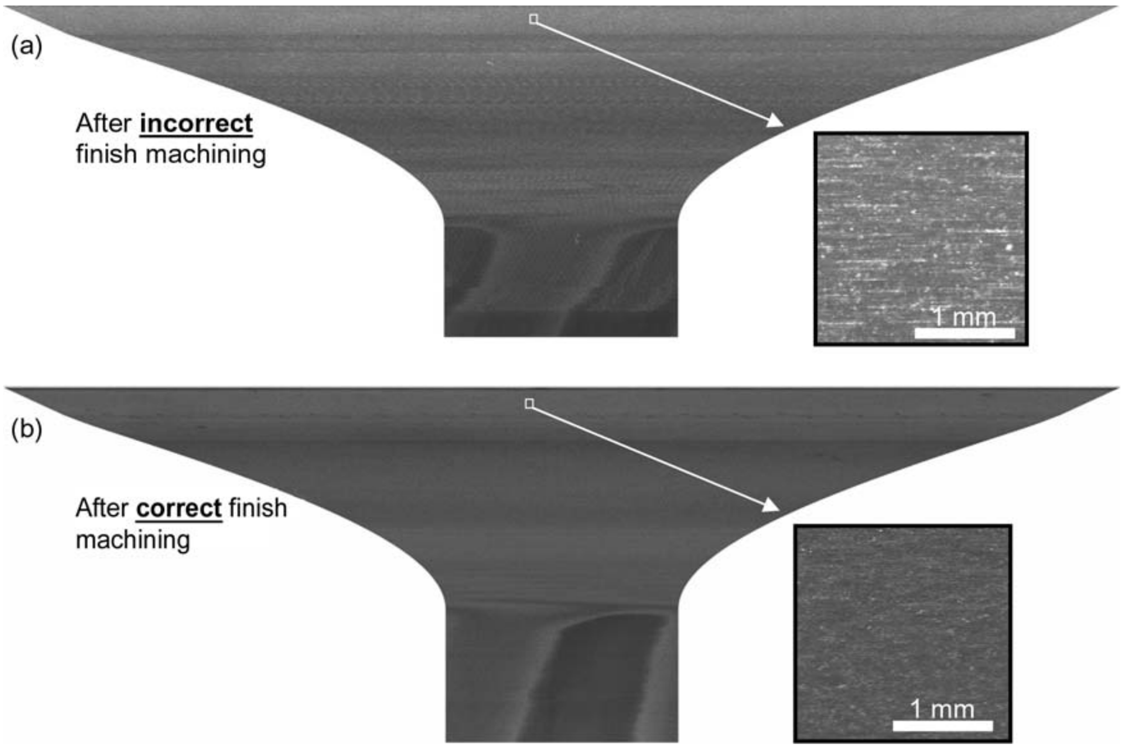

Figure 2. Laser scatter NDE scans of the same Si_3N_4 valve after poor finish machining (a) and after correct finish machining (b). Note that the machining defects (white streaks) are minimized after the valve is finish machined properly.

Valve engine testing

Arrangements have been made to perform engine tests at the National Transportation Research Center (NTRC) located in Oak Ridge, Tennessee. These tests will be executed with the intention to compare valve performance and reliability of advanced materials to current production materials. The valves will be tested on a Caterpillar G3406 natural gas genset platform. A G3406 cylinder head was outfitted with 32 thermocouples embedded in 4 intake and 4 exhaust valve seat inserts. Pressure transducers were installed in each of the six cylinders, the intake manifold and exhaust manifold. In addition, several custom valve train components have been designed to accommodate the modified valve design (i.e. thicker head, change in keeper geometry). Custom seat inserts, valve guides, keeper locks and bridges have been procured and are ready for installation in the G3406 engine.

A test plan has been generated to evaluate TiAl, Si_3N_4, and production valves performance in parallel. The material responses that will be studied are as follows: wear rates will be evaluated via profilometry and micrographic analysis; crack initiation and propagation will be evaluated using laser scatter and ultrasonic NDE; deposition formation will be evaluated via chemical analysis. The valves will be evaluated at various time intervals while accumulating 1000 h of engine test exposure.

As previously mentioned, the valves have been finish machined and are ready for on-engine evaluation (Figure 3). However, there must be an acceptable familiarity with the performance of these novel valve materials prior to evaluation on engine tests. Thus, a set of two Si_3N_4 intake valves and two TiAl exhaust valves is currently accumulating time on an impact test rig (20 h to date) to assess early life wear and crack propagation.

Valve modeling

To rigorously evaluate the performance of a component made from a brittle material, it is insightful to consider the component's lifetime as a function of thermal stresses, mechanical stresses, and the cyclic nature of these loads. With Caterpillar's input, Jadaan Engineering & Consulting has been developing a lifetime prediction model, using NASA

Figure 3. Finish valves ready for engine testing.

CARES/Life code, for a Si_3N_4 exhaust valve subjected to the typical stresses seen in a G3406 engine environment. The inputs to this code follow:

- FEA model to establish the valve geometry [Figure 4(a)]
- Mechanical boundary conditions as a function of crank angle [Figure 4(b)]
- Thermal boundary conditions
- Mechanical properties of the valve material

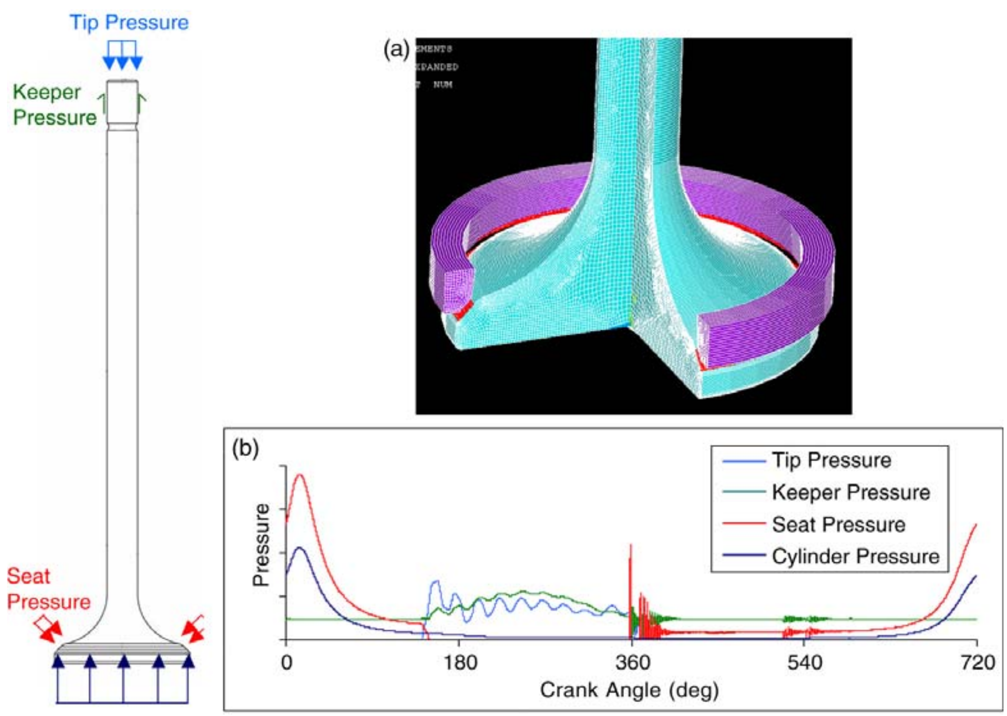

Figure 4. Inputs for the probabilistic life prediction model. (a) FEA valve model. (b) Mechanical boundary conditions as a function of crank angle.

These inputs were supplied to Jadaan Engineering & Consulting for a G3406 valve experiencing representative operating conditions. A FEA model was then generated, and a transient reliability analysis was performed. Subsequent to applying the mechanical and thermal boundary conditions onto the valve geometry, Si_3N_4 material properties are assigned to the elements. The mechanical load spectrum [Figure 4(b)] was discretized into a finite number of steps, and the stress state was calculated for each set of loads. Using the calculated stress fields, a computational transient reliability analysis is performed. In this approach, the material is susceptible to slow crack growth (fatigue) and the probability of failure depends on both the number of cycles and load history sequence. The probability of failure during a given time step is directly impacted by those in the previous time steps. Hence, because of fatigue damage the probability of failure will increase with time as damage accumulates with additional load cycles. The generated life prediction curve is shown in Figure 5. According to this curve, at a safety factor of three, there is <0.0001% probability of failure after 10 years of continuous operation! Although these results may seem to be extraordinarily promising, they must be interpreted with caution. Note that four loads that have been modeled are not the only loads present; they have only served to explore the model's capability. Further refinement of the valve's loading conditions must be made to model the valve's true operating conditions (i.e., non-axisymmetric bending loads). It is expected that when more rigorous boundary conditions are applied that the probability of failure will increase compared to this preliminary model.

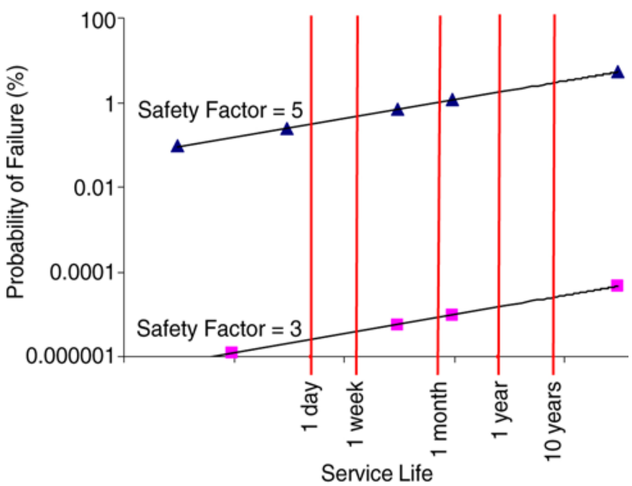

Figure 5. Life prediction curve generated from the preliminary probabilistic model. Safety factor represents the multiplication factor between the defined mechanical boundary conditions and the value used to calculate the probability of failure (i.e., if tip pressure was defined as 10 MPa; the set of data with safety factor = 5 used a tip pressure of 50 MPa).

In addition to refining the model's boundary conditions (i.e., implementing a 3-D model in place of the current axisymmetric model), several new capabilities will be added to the model. The model will be extended to enable the modeling of TiAl. Titanium aluminide will be modeled as a material with a 3-parameter Weibull distribution.[6] Also, the ANSYS/PDS (Probabilistic Design System) will be employed to evaluate the effect that model parameter variation (of e.g., dimensional tolerance, external loading, characteristic strength) has on the life prediction result.

Material characterization

Investigation of basic material properties and manufacturing considerations supplement the engine test and modeling effort. For instance, fundamental thermo-physical and mechanical data were collected on two varieties of TiAl and several varieties of Si_3N_4. The machinability of TiAl and Si_3N_4 and the friction coefficients of these materials are two subjects of particular interest.

Machining processes account for a significant portion of the cost of valve components. This is especially true for high-temperature materials such as intermetallics and ceramics because these materials show a greater sensitivity to surface features than metallic alloys. Thus, it is necessary to identify the most economical method of machining that achieves the required specifications (i.e., geometric tolerances, surface roughness). A series of experiments are planned that will investigate the capability of three machining techniques (turning, grinding, laser-assisted machining) on TiAl test specimens. The surface finish achieved by each technique will be quantified based on microscopy and profilometry measurements. These test specimens will then be subjected to axial stepped fatigue tests at room temperature and engine operating temperatures to evaluate the effect of machining damage and temperature on the fatigue performance of TiAl. These fatigue tests are to be performed at Oak Ridge National Laboratory.

Friction is a fundamental phenomenon in the valve train system. It behaves in both a detrimental manner (e.g., wear of valve seat contact) and beneficial manner (e.g., traction that allows retention of the rotocoil). There is currently no comprehensive database that captures the friction behavior of valve materials and their peripheral components. To address this, a matrix of experiments has been developed that will explore the interaction of various valve materials (TiAl, Si_3N_4 and austenitic steel) with the materials that they contact (seat insert, valve guide, keeper and bridge). These tests will be performed on an in-house Cameron-Plint test apparatus in an environment that matches the engine operating conditions as closely as possible. Results from these tests will aid modeling efforts and highlight the consequences of changing valve materials from the well-known production steel to an advanced material.

Conclusions

Lightweight, high-strength, high-temperature materials are enablers for advanced combustion concepts and fuel-efficient engine designs. This effort aims to examine two prospective materials, TiAl and Si_3N_4, in the context of heavy-duty diesel and natural gas engine environments. In this year progress has been made on several fronts: (1) toward conducting engine tests on these valve materials, (2) development of a probabilistic life prediction model, and (3) compilation of material properties of TiAl and Si_3N_4 that are critical to implementation of these materials in the extreme environment of a heavy-duty engine.

Twelve TiAl and forty-five Si_3N_4 valves have completed the fabrication process. Their incorrect surface finish provided by the machining supplier was rectified. The valves have been subjected to several preengine test characterization assessments: CMM, profilometry and laser-scatter NDE. The first set of valves has accumulated 20 h on an impact rig and has demonstrated acceptable performance. Upon successful completion of the impact rig test, the valves will be tested on a Caterpillar G3406 engine at the NTRC. In addition to fabricating custom components that will enable this engine to accept the new modified valve design, the engine has been instrumented to capture the performance of each cylinder.

Significant progress has been made toward developing a NASA CARES/Life prediction model. A preliminary model has been developed, and a life prediction curve has been generated. It was speculated that this preliminary curve significantly underpredicts the probability of failure due to incomplete representation of the boundary conditions. Model enhancements are currently underway and updated results will be correlated to the engine performance of the valve hardware.

Thermo-physical properties (e.g., coefficient of thermal expansion, thermal conductivity, density) and mechanical properties (e.g., ultimate tensile strength, Young's modulus, ductility) of TiAl and Si_3N_4 have been collected. Properties specific to implementation of these advanced materials in a valve environment are also under investigation (e.g., machinability, frictional coefficients, corrosion resistance).

This diverse effort will help to equip design engineers with the information required to implement advanced lightweight materials in a valve train application. This program has made significant progress toward this goal in FY 2005 and is poised to significantly advance the case for TiAl and/or Si_3N_4 as a future valvetrain material in FY 2006.

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Presentations and Publications

J. M. Zhang, J. G. Sun, M. J. Andrews, A. Ramesh, J. S. Trethewey, and D. M. Longanbach, "Characterization of subsurface defects in ceramic rods by laser scattering and fractography," presented at the 32nd Annual Review of Progress in Quantitative Nondestructive Evaluation, Bowdoin College, Brunswick, Maine, July 31–August 5, 2005, and paper to be published in conference proceedings.

J. G. Sun, J. M. Zhang, J. S. Trethewey, J. A. Grassi, M. P. Fletcher, and M. J. Andrews, "Nondestructive evaluation of machining and bench-test damage in silicon nitride ceramic valves," paper presented at the American Ceramic Society's 29th Ann. Intl. Cocoa Beach Conf. & Exposition on Advanced Ceramics & Composites, Cocoa Beach, Florida, January 23–28, 2005, and to be published in conference proceedings.

J. S. Trethewey, H.-T. Lin, and J. G. Sun, "Lightweight valve train materials," presented at Department of Energy Merit Review, Oak Ridge National Laboratory, September 15, 2005.